Two-phase and gaseous cryogenic avalanche detectors based on GEMs

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Outline

- Motivation: coherent neutrino scattering, dark matter search, solar neutrino detection, medical applications
- Gaseous cryogenic avalanche detectors above 78 K
- Two-phase avalanche detectors: in Ar, Kr and Xe
- Cryogenic avalanche detectors at low T, below 78 K: in He and Ne
- Summary

In this field we collaborate with

V. Kudryavtsev, P. Lightfoot, N. Spooner, D. Tovey
Sheffield University

J. Dodd, R. Galea, Y. Ju, M. Leltchouk, W. J. Willis
Columbia University (Nevis Lab)
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BNL

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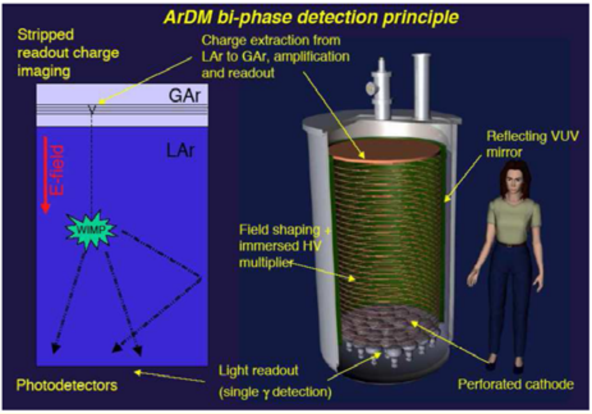
Motivation: cryogenic detectors for coherent neutrino scattering, dark matter and solar neutrino detection



Two-phase Ar detectors for dark matter search using thick GEM readout

Rubbia et al., Eprint hep-ph/0510320

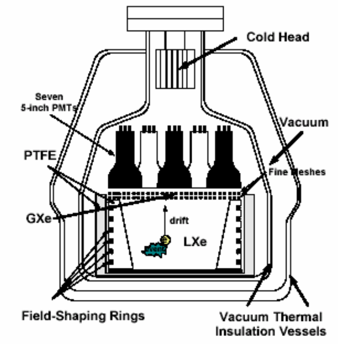
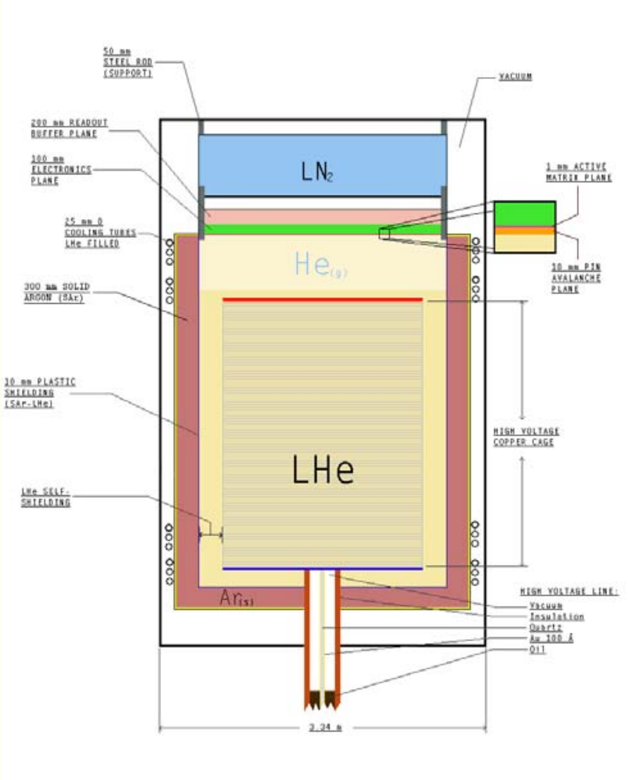


Fig. 1. A schematic diagram of the ZEPLIN II central detector with vacuum thermal insulation vessels, wire meshes, and field-shaping copper wires.

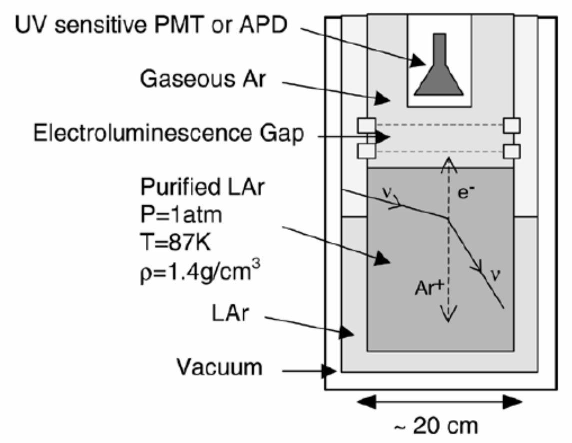
Two-phase Xe detectors for dark matter search

ZEPLIN II-IV *[UK Dark Matter Search Collaboration]*, XENON *[Aprile et al. Eprint astro-ph/0407575]*



Two-phase He or Ne detectors for solar neutrino detection using charge readout

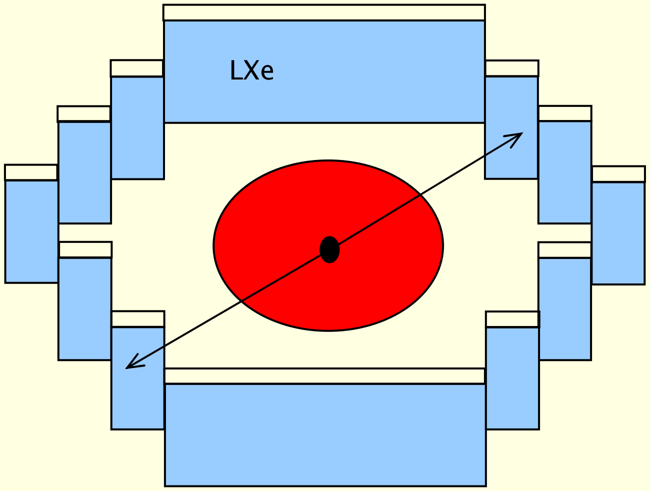
Columbia Univ (Nevis Lab) & BNL, www.nevis.columbia.edu/~ebubble



Two-phase or high-pressure Ar or Xe detectors for coherent neutrino-nucleus scattering

Hagmann & Bernstein, IEEE Trans. Nucl. Sci. 51(2004)2151; Barbeau et al., IEEE Trans. Nucl. Sci. 50(2003)1285

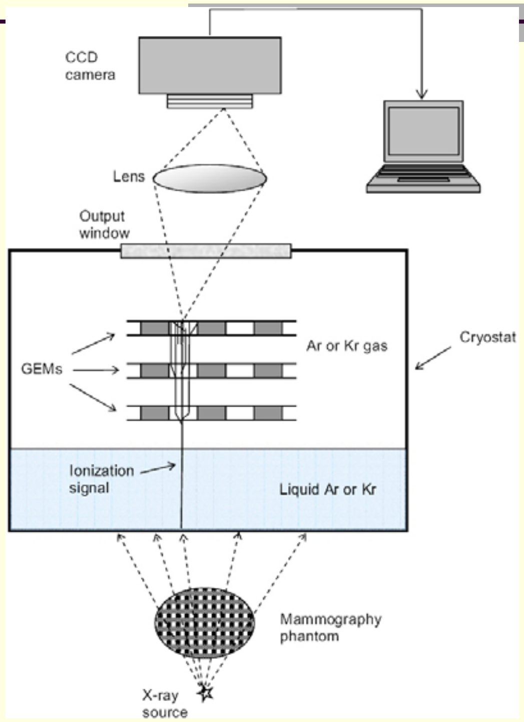
Motivation: cryogenic two-phase detectors for medical applications

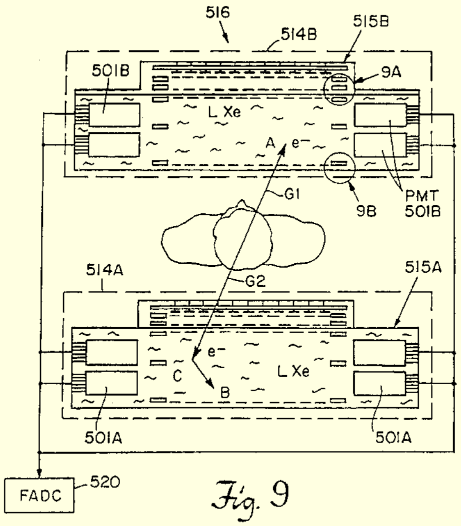


GEM-based two-phase Xe or Kr avalanche detector for PET

- Solving parallax problem
- Superior spatial resolution if to use GEM readout

Budker Institute: CRDF grant RP1-2550 (2003)





Two-phase Xe detector for PET

Chen & Bolozdynya, US patent 5665971 (1997)

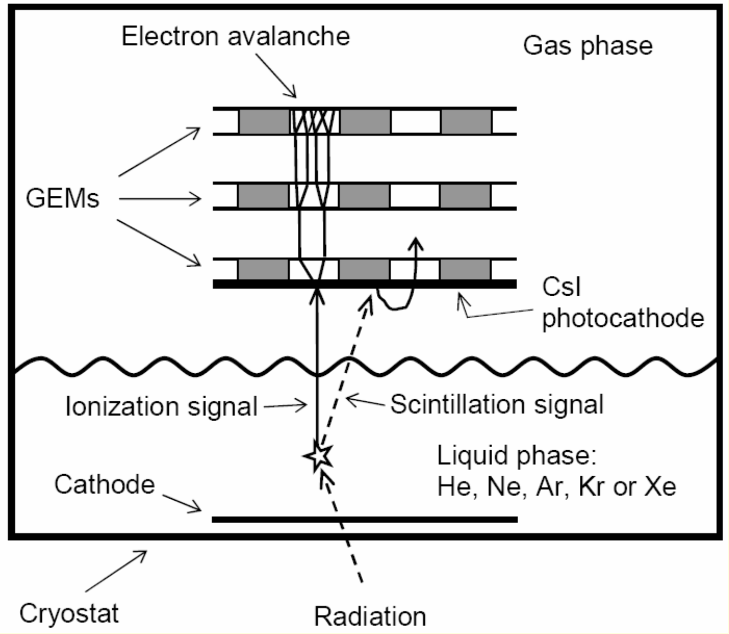
GEM-based two-phase Ar or Kr avalanche detector for digital radiography with CCD readout

- Robust and cheap readout
- Thin (few mm) liquid layer is enough to absorb X-rays
- Primary scintillation detection is not needed

Budker Institute: INTAS grant 04-78-6744 (2005)

Principles of two-phase avalanche detectors based on GEMs

- Primary ionization (and scintillation) signal is weak: of the order of 1, 10, 100 and 500 keV for coherent neutrino, dark matter, solar neutrino and PET respectively
→ Signal amplification, namely electron avalanching in pure noble gases at cryogenic temperatures is needed
- Detection of both ionization and scintillation signals in liquid might be desirable, the latter - to provide fast signal coincidences in PET and to reject background in neutrino and dark matter detection
- Electron avalanching at low temperatures has a fundamental interest itself

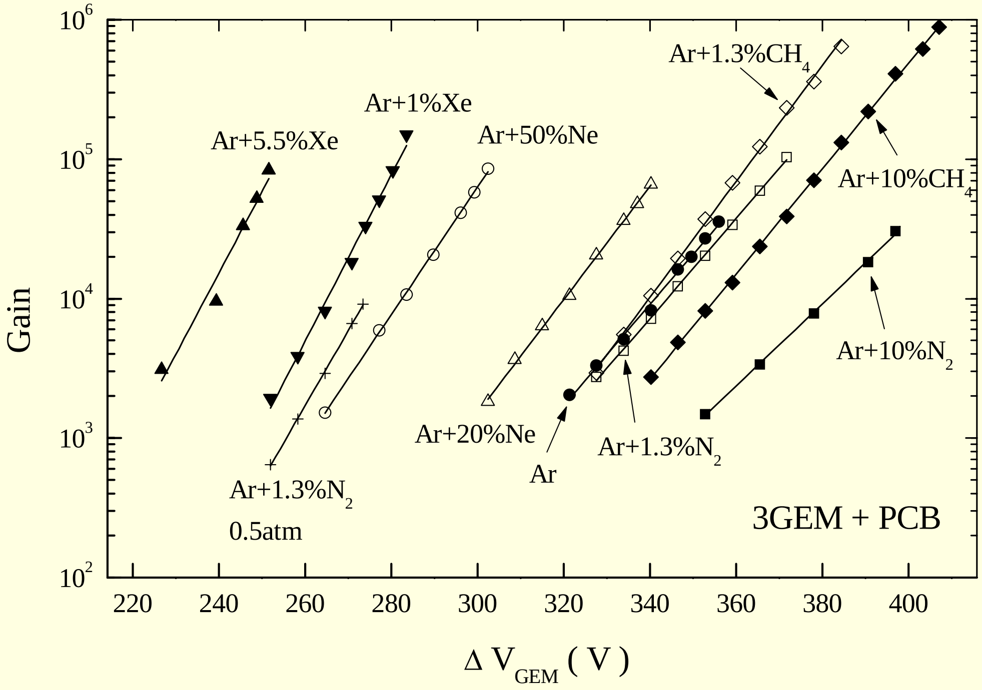


The concept of two-phase (liquid-gas) or high pressure cryogenic avalanche detector using multi-GEM multiplier, with CsI photocathode on top of first GEM

1. Buzulutskov et al., First results from cryogenic avalanche detectors based on GEMs, IEEE Trans. Nucl. Sci. 50(2003)2491
2. Bondar et al., Cryogenic avalanche detectors based on GEMs, NIM A 524(2004)130.
3. Bondar et al., Further studies of two-phase Kr detectors based on GEMs, NIM A 548(2005)439.
4. Buzulutskov et al., GEM operation in He and Ne at low T, NIM A 548(2005)487.
5. Bondar et al., Two-phase Ar and Xe avalanche detectors based on GEMs, NIM A 556(2006)237
6. Galea et al., Gas purity effect on GEM performance in He and Ne at low T, Eprint arxiv.org/physics/0602045

Unique advantage of GEMs and other hole-type structures: high gain operation in “pure” noble gases

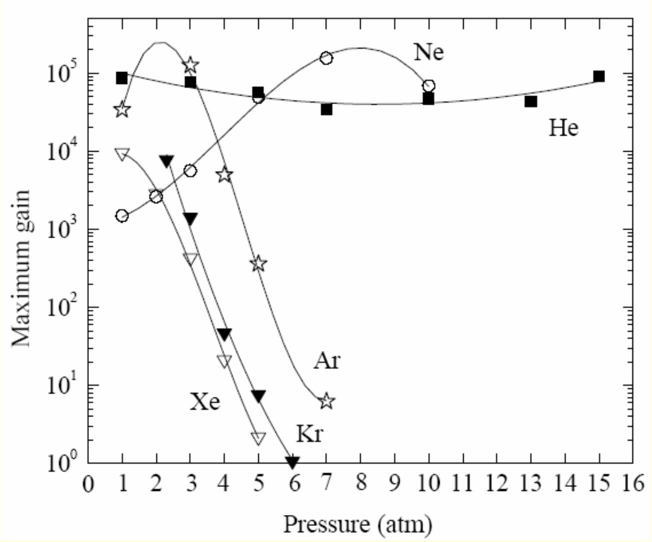
GEM: Gas Electron Multiplier *[Sauli, NIM A 386(1997)531]*



3GEM operation in Ar-based noble gas mixtures at 1 atm and room T

- Rather high gains, exceeding 10^5, are reached

Budker Inst & Weizmann Inst & CERN: NIM A 443(2000)164



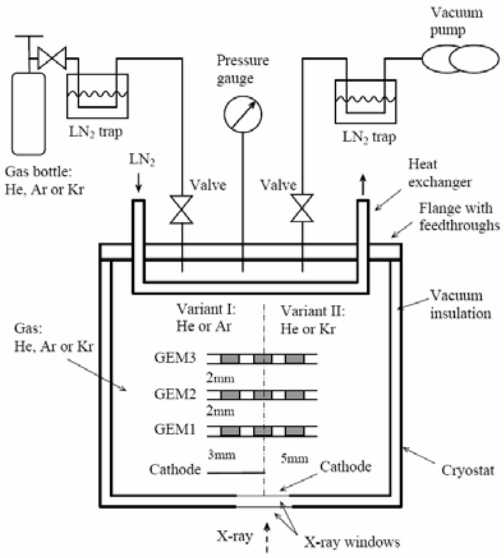
3GEM operation in noble gases at high pressures at room T

- In heavy noble gases: high gain (~10^4) operation at 1 am and fast gain decrease at higher pressures.

- In light noble gases: high gain (~10^5) operation at high pressures

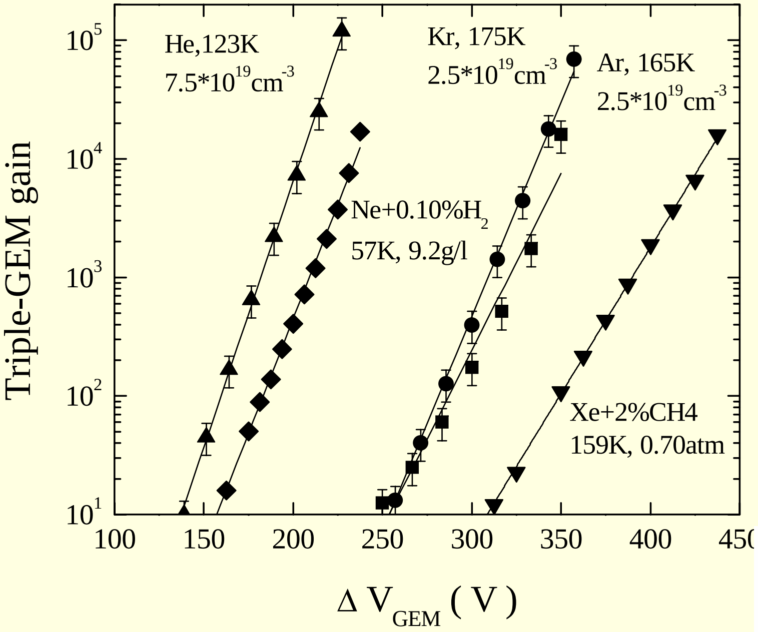
Budker Inst: NIM A 493(2002)8; 494(2002)148
Coimbra & Weizmann Inst: NIM A 535(2004)341

Gaseous cryogenic avalanche detectors based on GEMs



Experimental setup

- Operated in He, Ar, Kr and Xe
- 2.5 l cryogenic chamber

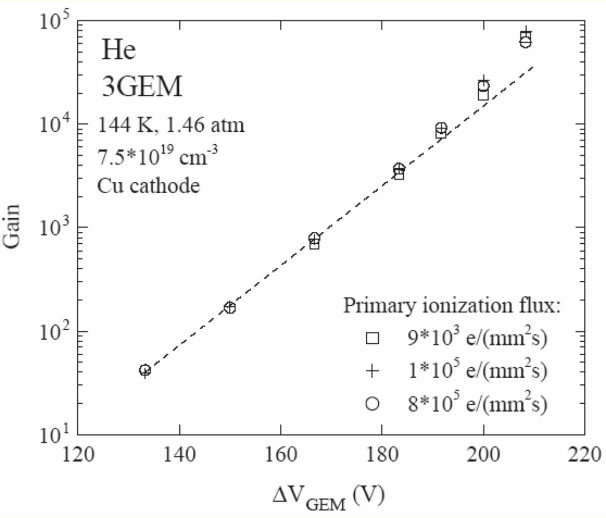


3GEM operation at cryogenic T in different gases

- Rather high gains are reached at cryogenic T: the maximum gain exceeds 10^5 in He and 10^4 in Ar, Kr and $Xe+CH_4$

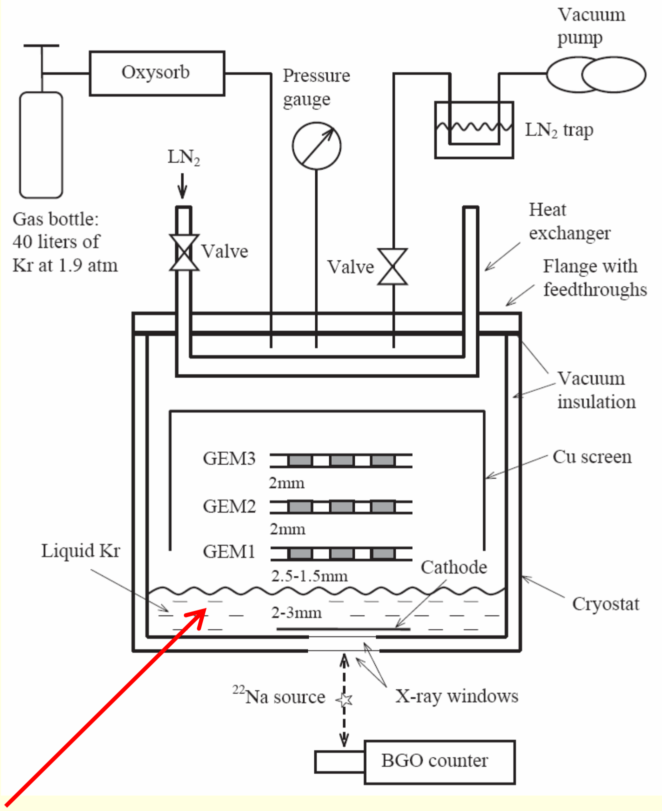
3GEM operation at cryogenic T at different fluxes

- No charging-up effects were observed in He, even at fluxes as high as 10^6 e/mm^2 s

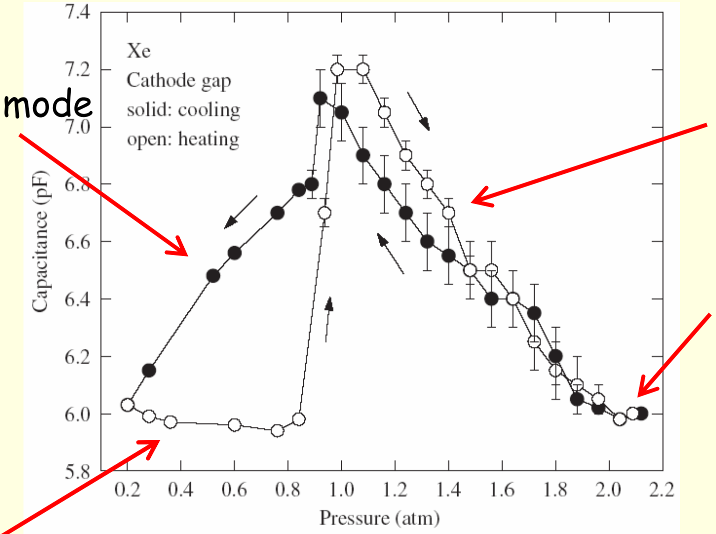


Two-phase avalanche detectors based on GEMs: experimental setup

- *Developed at Budker Institute*
- 2.5 l cryogenic chamber
- Operated in Ar, Kr and Xe
- Liquid thickness 3-11 mm
- Liquid purity: electron drift path about 10 mm in Ar, 3 mm in Kr and 1 mm in Xe
- 3GEM+PCB assembly inside
- Irradiated with pulsed X-rays, beta-particles and gamma-rays



Liquid layer
thickness 3-12 mm



Solid-gas mode

Liquid-gas mode

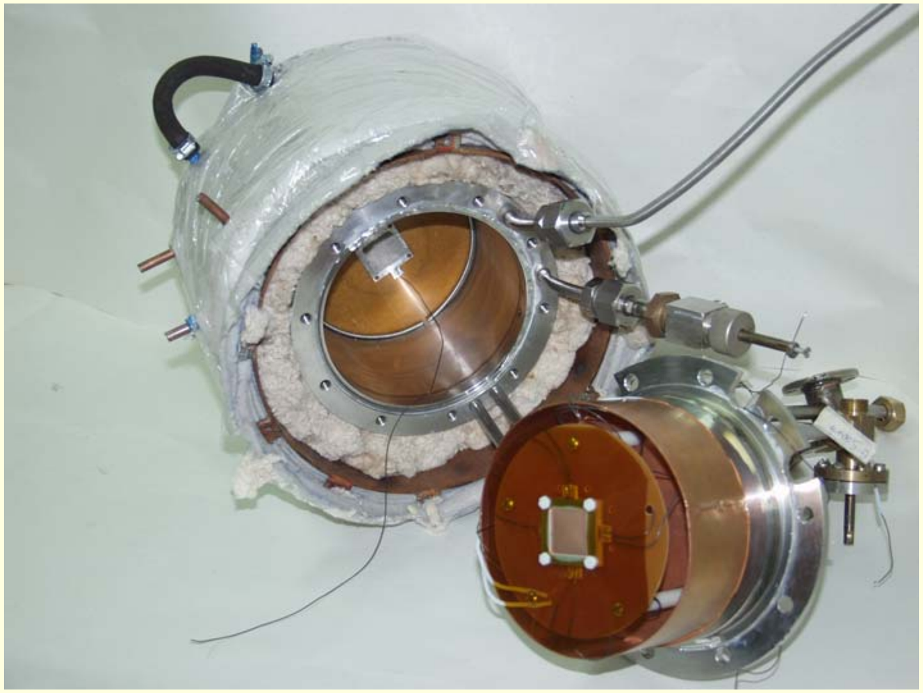
Gaseous mode

Gaseous mode

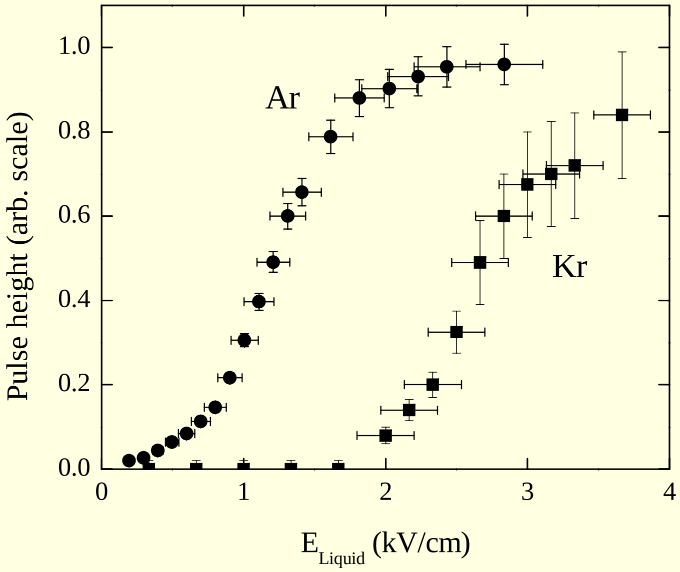
Cathode gap capacitance as a function of pressure in Xe during cooling-heating procedures

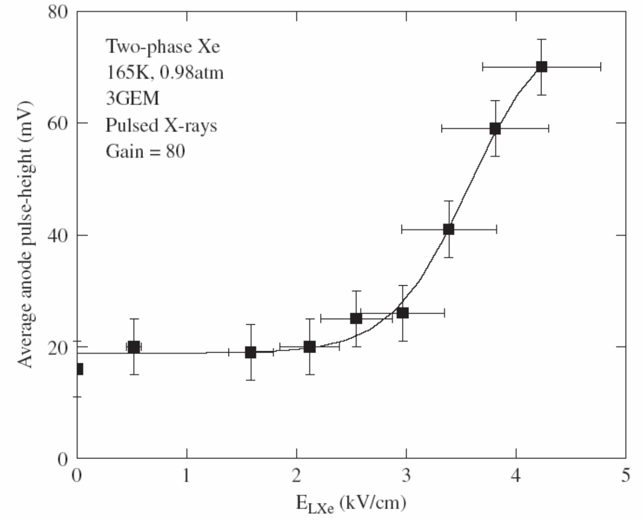
Two-phase avalanche detector: experimental setup

- 2.5 l cryogenic chamber
- 10 l chamber is under construction



Two-phase avalanche detectors: electron emission through liquid/gas interface





Emission characteristics in Ar and Kr

- Anode pulse-height as a function of electric field in the liquid induced by beta-particles: in Ar – in 2 GEM at gain 1500; in Kr – in 3 GEM at gain 250.

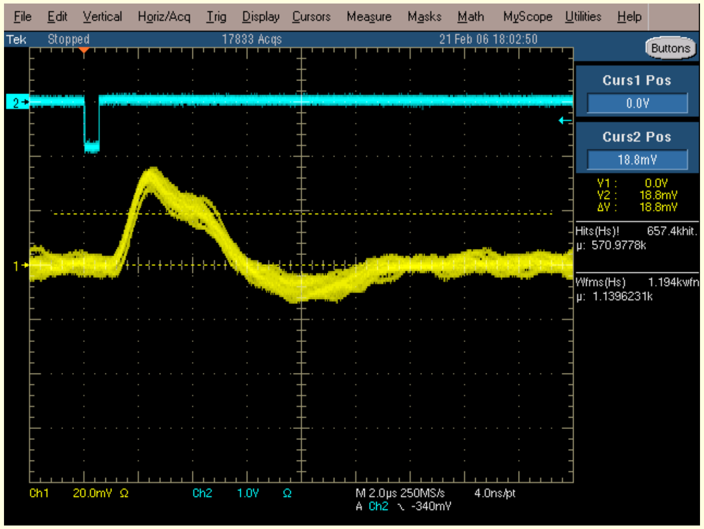
Emission characteristics in Xe

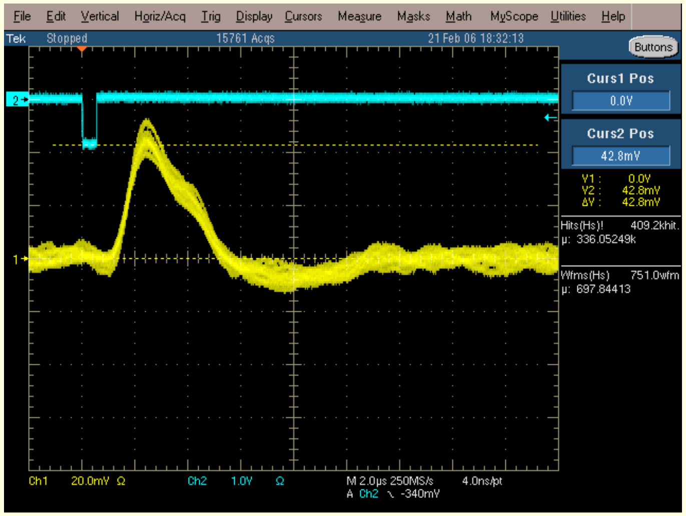
- Anode pulse-height as a function of electric field in liquid Xe induced by pulsed X-rays, in 3 GEM at gain 80.

- Electron emission from liquid into gas phase has a threshold behavior
- Electric field for efficient emission: in Ar by a factor of 2-3 lower than that in Kr and Xe

Two-phase Ar avalanche detector: calibration signals

Anode signals induced by pulsed 40-50 keV X-rays recorded at the first GEM electrode



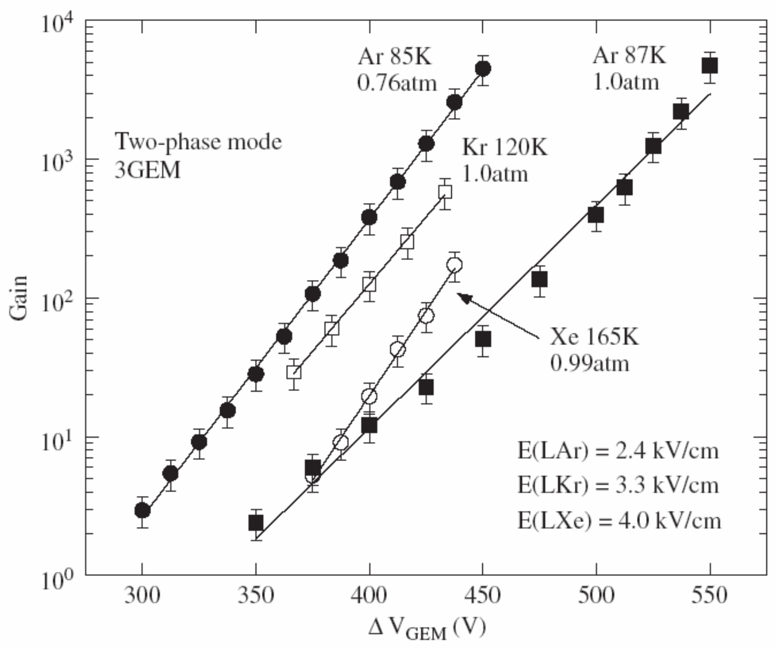


- Liquid layer thickness 6 mm
- Electric field ~2 kV/cm
- Shaping time 0.5 µs

- Liquid layer thickness 8 mm
- Electric field ~2 kV/cm
- Shaping time 0.5 µs

Pulses have trapezium shape: this is due to electron attachment in the liquid (ideal pulse would have rectangular shape with width proportional to layer thickness) → rough estimation of electron drift path

Two-phase avalanche detectors: gain characteristics



- Two-phase mode, 3 GEM, pulse counting mode

- **In Ar**: rather high gains are reached, of the order of 10^4,

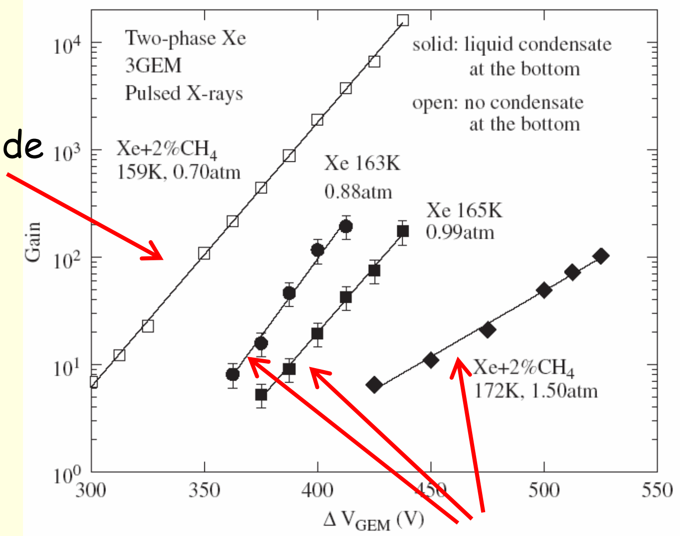
- **In Kr and Xe**: moderate gains are reached, about 10^3 and 200 respectively

- Electron avalanching in saturated vapor does not differ from that of normal gas in general

- Gain and voltages are similar to gaseous mode at equal gas densities

- However, in Kr and Xe the maximum gain in two-phase mode is substantially lower than that in gaseous mode at cryogenic T

Gaseous mode

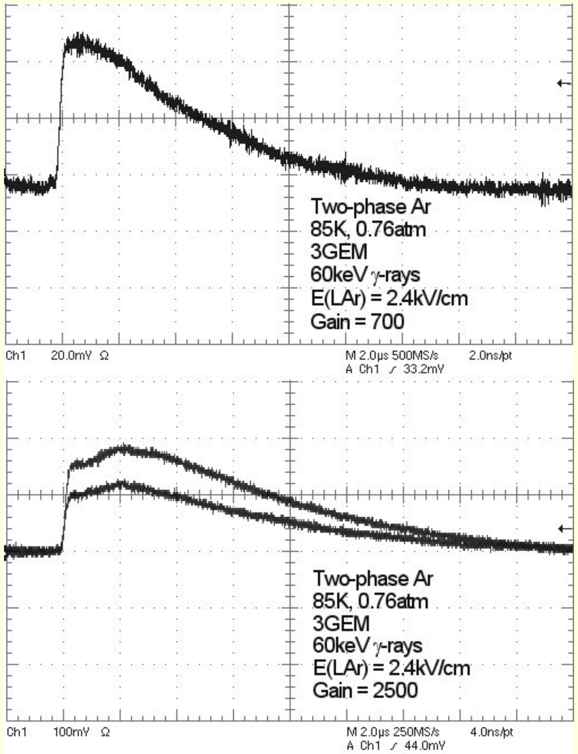


Two-phase mode

- **In Xe**: adding CH_4 does not help to increase the gain

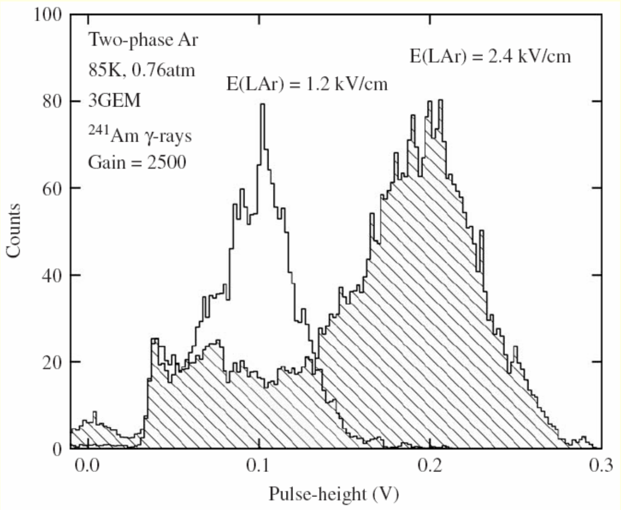
- Just operation in two-phase mode imposes a principal limit on the maximum gain?

Two-phase Ar avalanche detector: pulse shape and energy resolution



- Two-phase Ar, 3 GEM, 60 keV gamma-rays from ^{241}Am, gain 700 (top) and 2500 (bottom)

- At higher gains the primary signal is accompanied by secondary signal: presumably due to photon feedback between GEMs



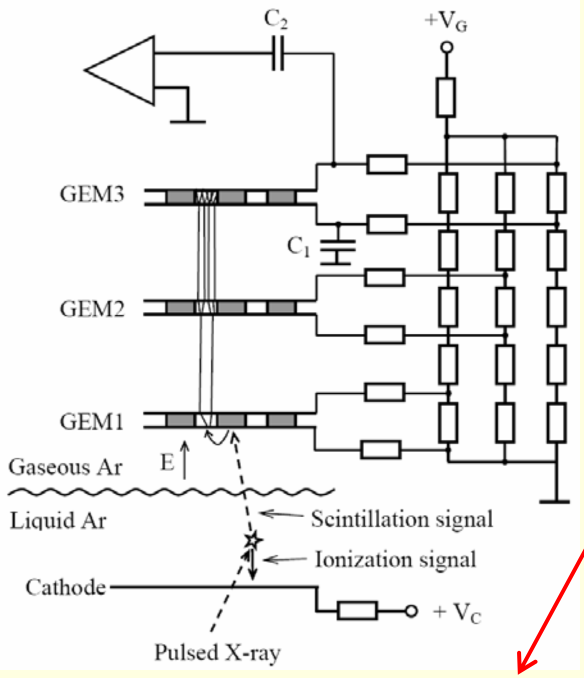
- Two-phase Ar, 3 GEM, 60 keV gamma-rays from ^{241}Am, gain 2500

- Distinct peak + tail (presumably due to scattered photons) are seen

- Effect of extraction field is well pronounced

- Energy resolution, 37% FWHM, is defined mostly by pressure variations: expected to be improved in detectors with better T stabilization

Two-phase Ar avalanche detector: single electron counting mode



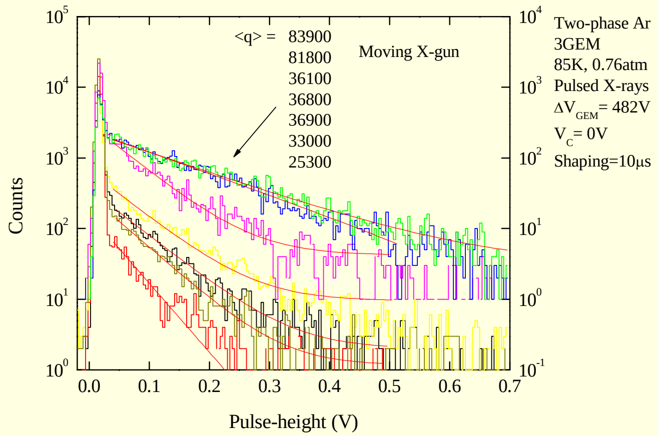
- 10 mm liquid layer, 3GEM, pulsed X-rays

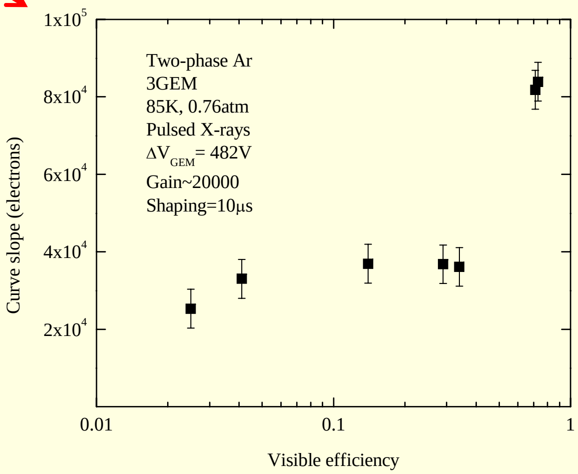
To obtain single electron counting mode:

- Reversing drift field to suppress ionization signal
- Detecting photoemission signal from Cu electrode of GEM1, induced by scintillation signal
- Moving X-ray gun away to have:

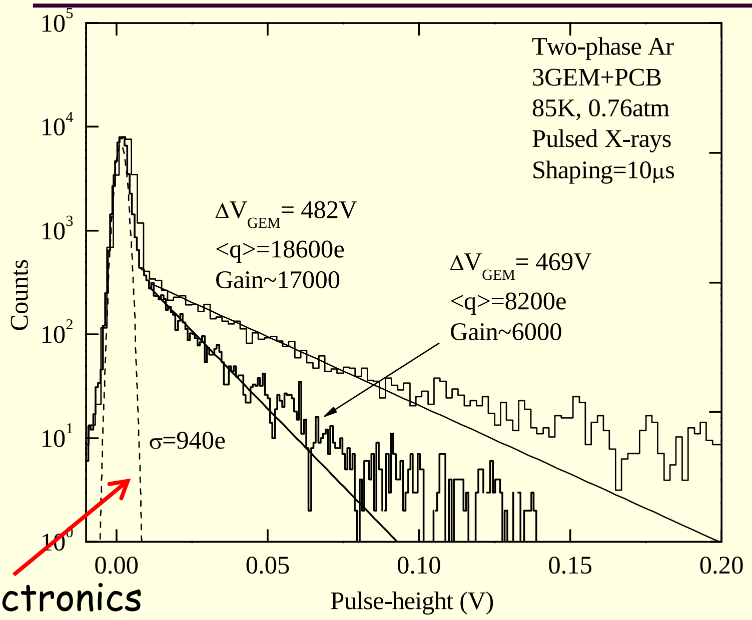
a) pulse-height curve slope does not change any more

b) detection efficiency is much below 1

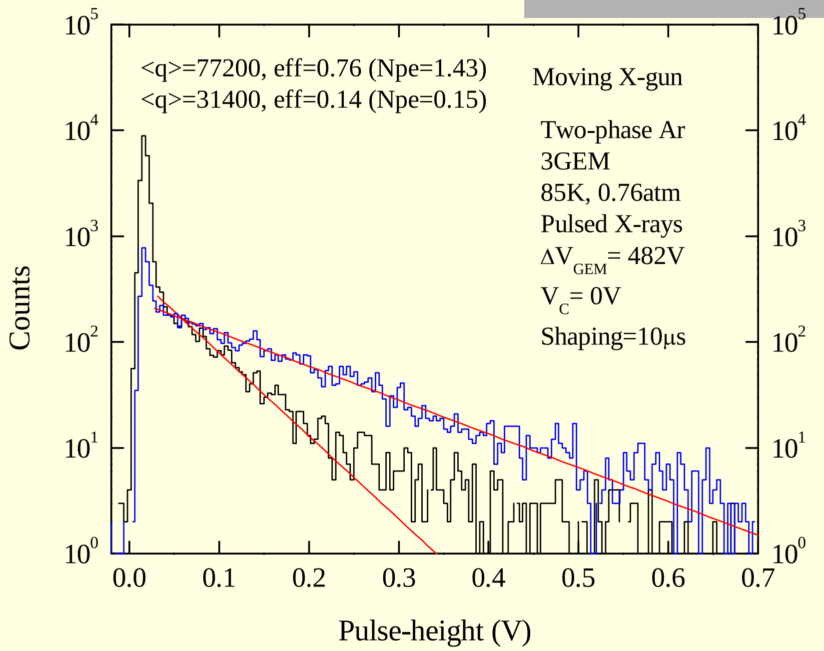




Two-phase Ar avalanche detector: single electron counting mode



Electronics noise spectrum



Single electron pulse-height spectra

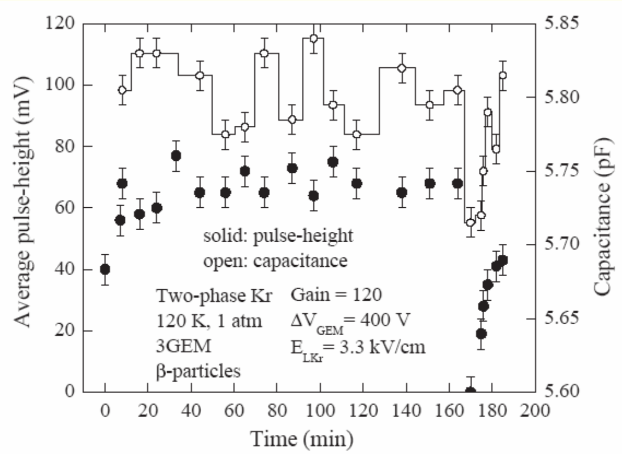
- At gain 6000 and 17000, in 3GEM+PCB
- Spectrum shape is exponential: typical for electron avalanching in gas media

Pulse-height spectra for single and 1.4 electron

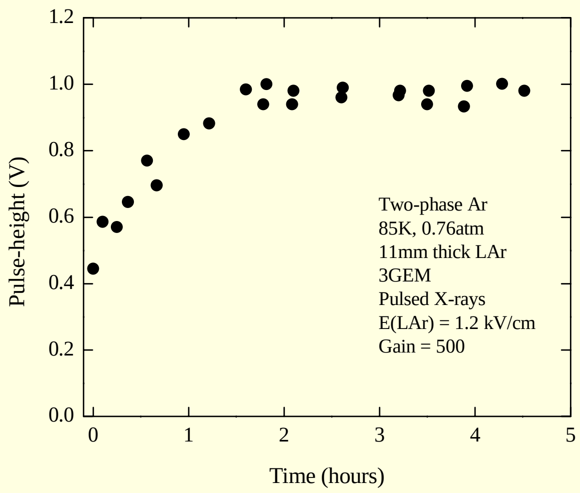
- At gain 30000, in 3GEM.
- Single and two electron events would be well distinguished by spectra slopes

Rather high GEM gains (tenths of thousands) and stable operation obtained in two-phase Ar allow to operate in a single electron counting mode, corresponding to sensitivity to deposited energy of as low as 24 eV

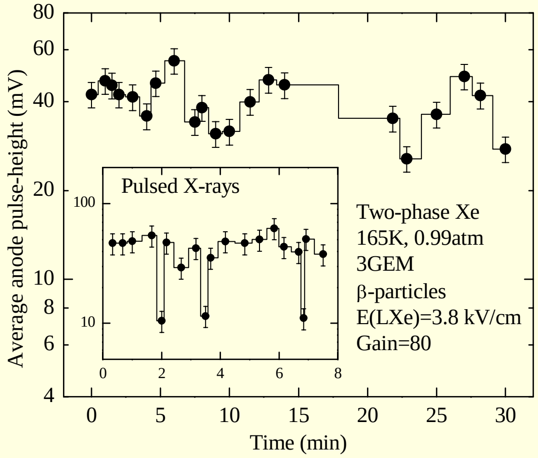
Two-phase avalanche detectors: stability of operation



- **Two-phase Kr**, 3GEM, gain 120, beta-particles
- Relatively stable operation for 3 hours



- **Two-phase Ar**, 3GEM, gain 500, pulsed X-rays, liquid thickness 11 mm
- Relatively stable operation for 5 hour
- Gain increase during first 1.5 h is probably correlated to gradual pressure decrease due to temperature stabilization process

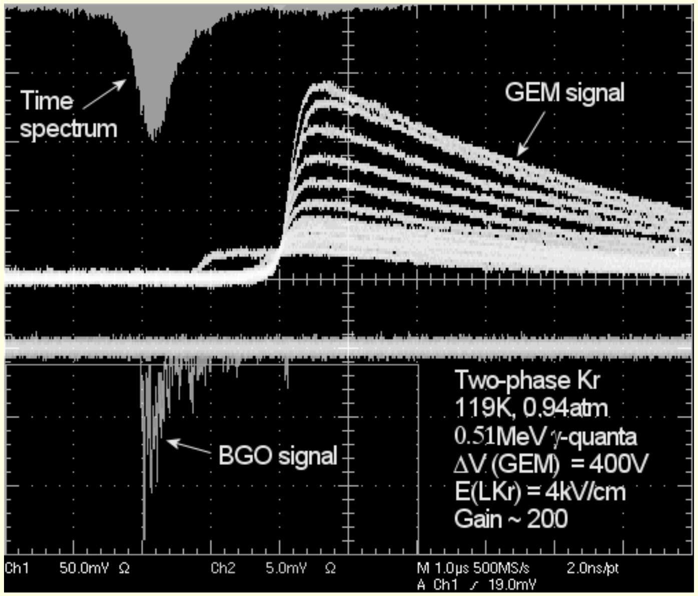


- **Two-phase Xe**, 3GEM, gain 80, liquid thickness 3 mm
- Relatively stable operation for 0.5 hour when irradiated with beta-particles
- Short-term (few sec) instabilities when irradiated with pulsed X-rays
- On the other hand, *Lightfoot et al NIM A 554 (2005) 266* observed that signal disappeared in ~10 min in two-phase Xe+CH_4 with Micromegas readout

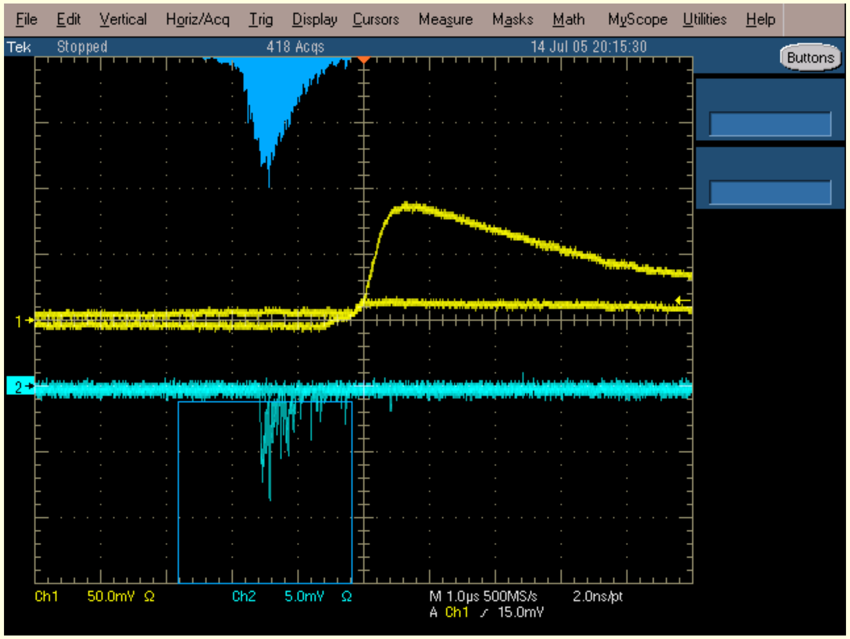
In Ar and Kr: possibility for stable GEM operation in avalanche mode in saturated vapor is confirmed
In Xe: further studies are needed

Two-phase Kr and Xe avalanche detectors: towards PET applications.

Anode signals from 3GEM induced by 511 keV collinear γ-quanta from ^{22}Na in coincidences with BGO counter, triggered by GEM signal

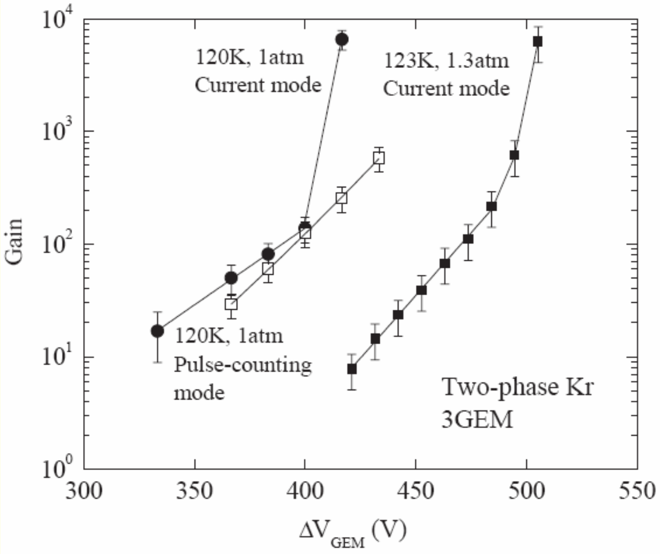


- **Two-phase Kr**, liquid layer 3 mm
- 3GEM at gain 200.
- Almost no background
- GEM-BGO signal delay is t~2 µs: corresponds to electron drift time in liquid and gaseous Kr in the gap and between GEMs



- **Two-phase Xe**, liquid layer 3 mm
- 3GEM at gain 80

Two-phase avalanche detectors: secondary effects (not understood)

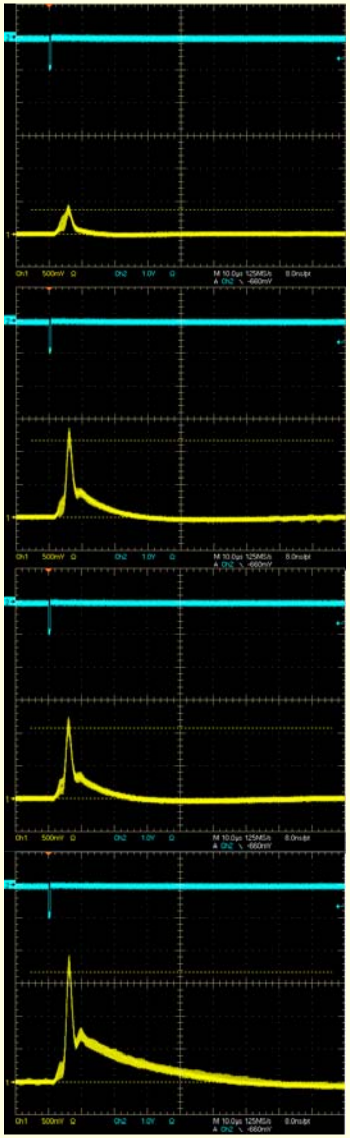


Charging-up effects?
In two-phase Kr in current mode, secondary effects arise at higher gains: current increases with voltage faster than exponentially. They are not observed in a pulse-counting mode. Most probably they are induced by ion feedback.

Ion feedback effects?
In two-phase Ar at larger LAr thickness (8 mm), secondary effects arise at higher extraction fields and gains: the primary signal is periodically changed, being accompanied by delayed secondary signal.

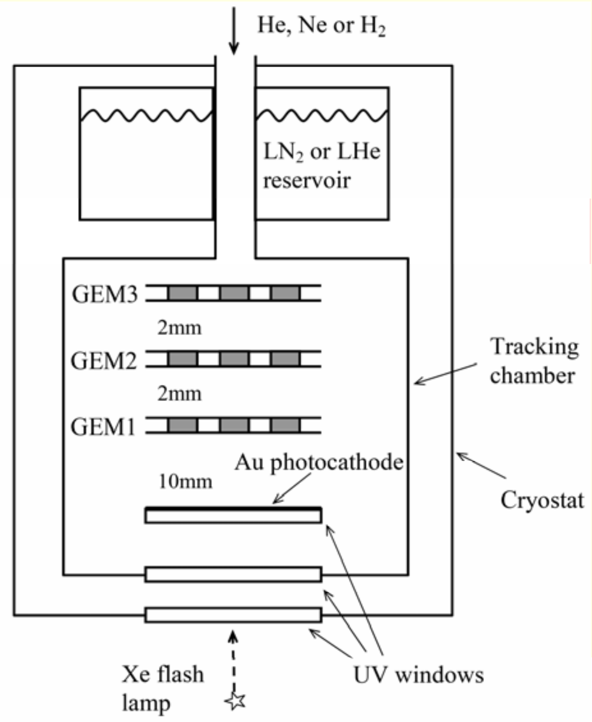
- 3GEM, pulsed X-rays, 240 Hz, Vg=3600V, Vc=2400V, E(LAr)~2kV/cm, shaping time 0.5 μs,
- Evolution cycle 11-12 sec

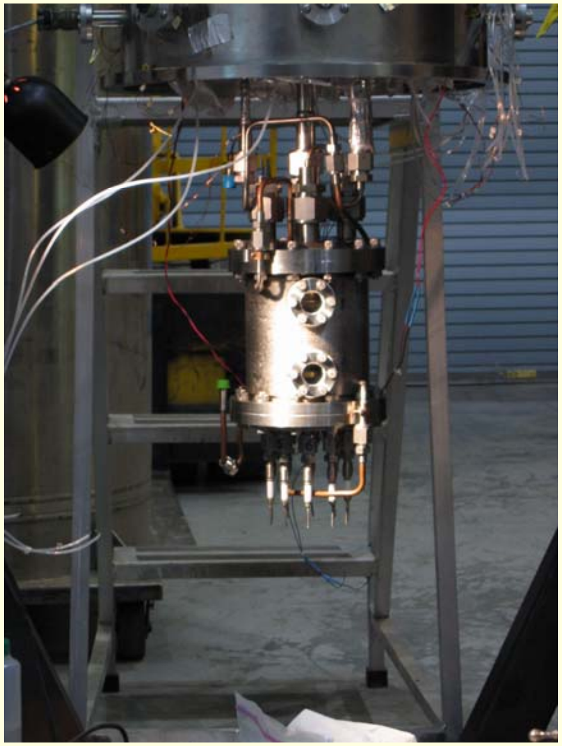
Possible interpretation: field screening by ion space charge, accumulated in the liquid layer due to low ion drift velocity (~1cm/sec) and high ion feedback current from GEMs.



High rate operation in two-phase avalanche detectors, in particular in PET, is under question?

Cryogenic avalanche detectors at low T: experimental setup

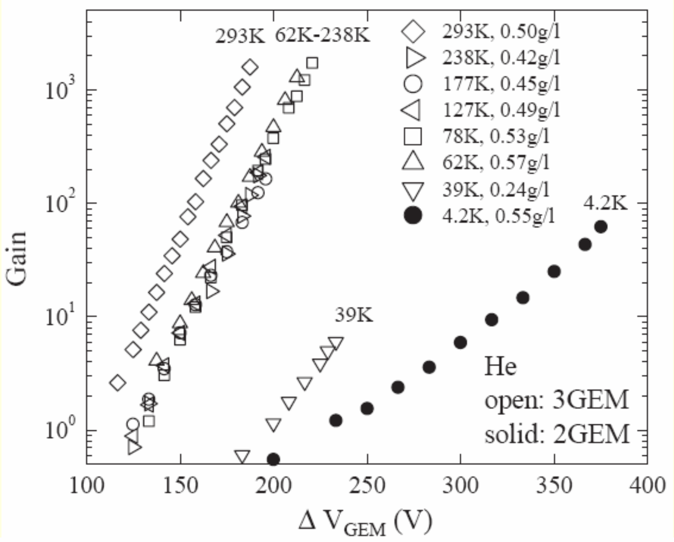


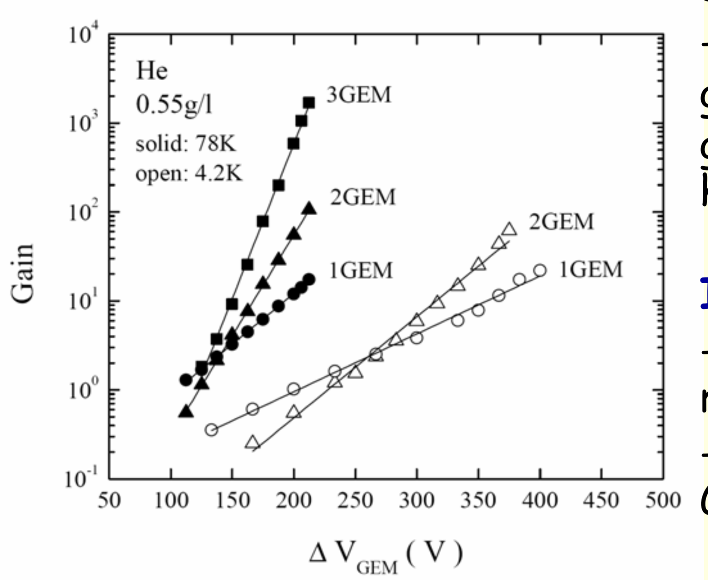


Experimental setup:

- *Developed at Columbia University (Nevis Lab) & BNL*
- Operated in He and Ne
- 1.5 l cryogenic chamber
- Several UV windows
- 3GEM inside
- Gas filling through LN_2 or LHe reservoir

Gaseous cryogenic avalanche detector at low T: gain and pulse shape characteristics in He



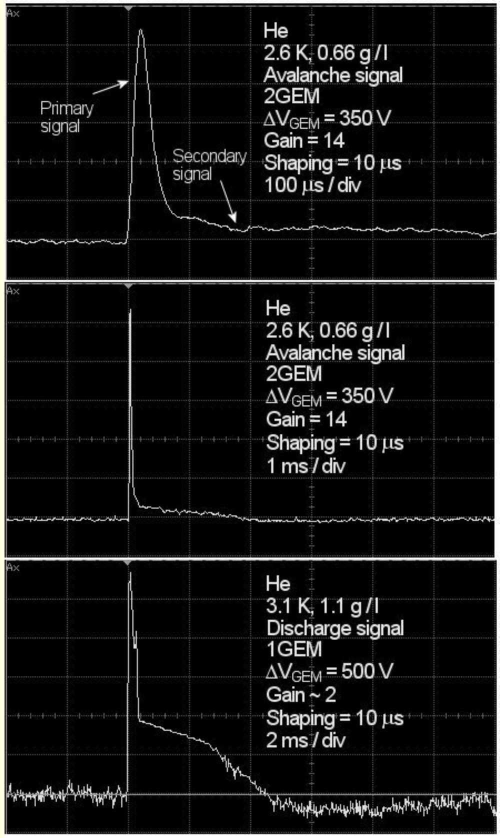


In He:

- High gains in 3GEM at T > 78 K
- Operation voltages increased when changing the cooling medium in reservoir
- Below 30 K, 3GEM could not work at all; only 2GEM and 1GEM could operate in avalanche mode
- At 2.6-20 K maximum gain is only few tens at 0.5 g/l and drops further at higher densities

In Ne:

- High gains in 3GEM at room T
- However at cryogenic T, GEMs could not work at all



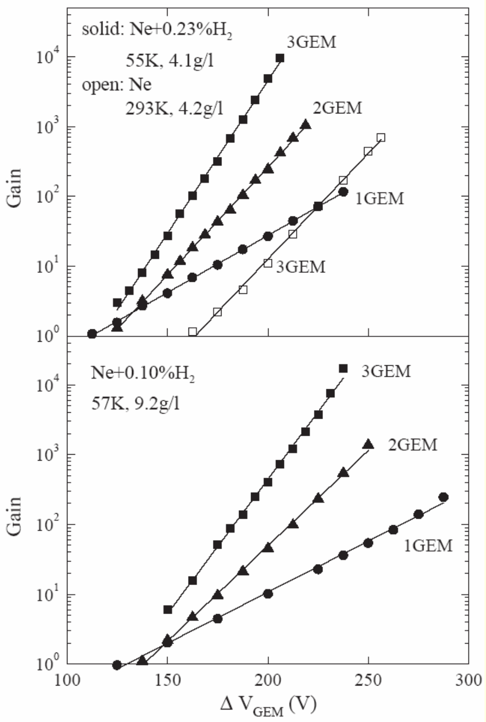
At low T, below 4 K, the primary signal is accompanied by secondary signal with width reaching few ms. Effect of metastable states?

Solution of the gain drop problem at low T: using Ne+H_2 Penning mixture

Ne forms Penning mixture with H_2 at low T:

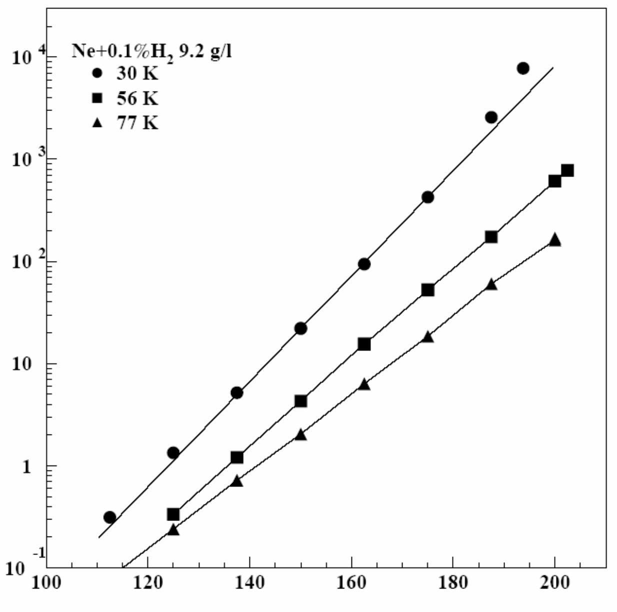
- H_2 boiling point (20 K) is below that of Ne (27 K)
- Energy of metastable Ne state exceeds H_2 ionization potential

This is a solution of the gain drop problem at low T in Ne. Unfortunately, this does not work for two-phase He, since H_2 vapor pressure is too low at He boiling point (4.2 K)



Gains in Ne+H_2 at 55-57 K

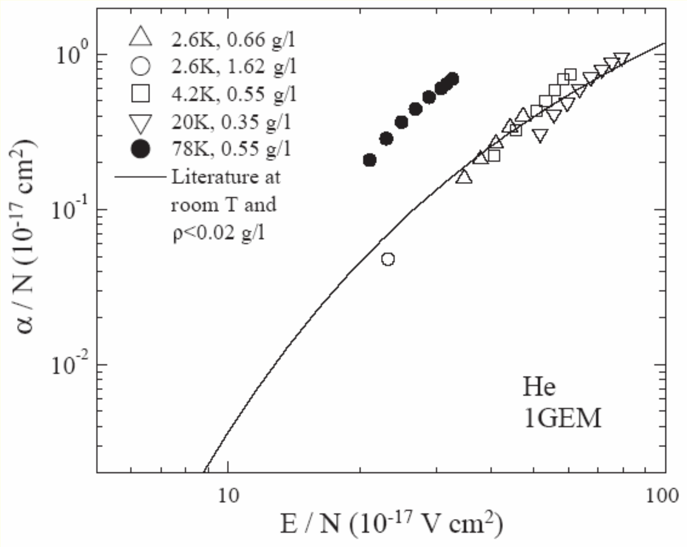
- at density 4 and 9 g/l, the latter corresponding to saturated vapor density at Ne boiling point
- Rather high gains are observed, as high as $2*10^4$. The maximum gains are not reached here!



Gains in Ne+H_2 at 30-77 K

- at density 9 g/l *[Galea et al., Eprint arxiv.org/physics/0602045]*

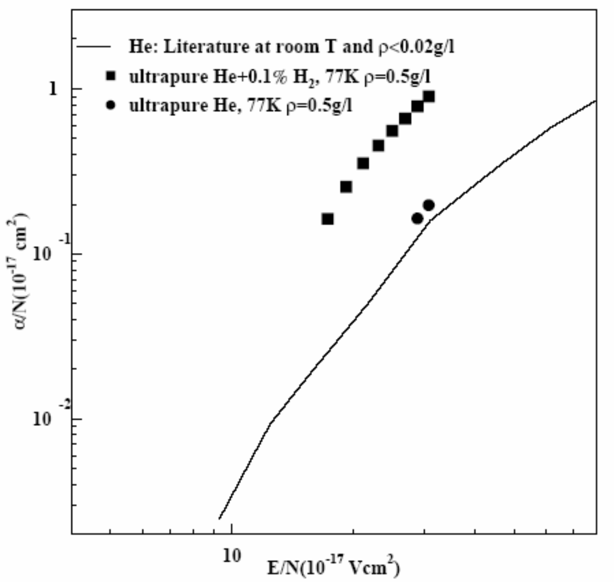
High gain operation in He (and Ne) above 77 K is due to Penning effect in impurities?



Ionization coefficients as a function of the electric field in dense He, obtained from 1GEM data, at 2.6-20 K and 78 K.

- He taken from bottle with quoted impurity content 10^{-5}

- Compared to literature data at room T and low density



Ionization coefficients for ultrapure He and He+$10^{-3}$$H_2$, obtained from 2GEM data, at 78 K

- He was additionally purified when filling the chamber (Oxisorb + getter)

- Impurity content 10^{-6}

[Galea et al., Eprint arxiv.org/physics/0602045]

Ionization coefficients for ultrapure He and He "purified" by low T (< 20 K) correspond to literature data. That means that the principal avalanche mechanisms at room and low T are the same (electron impact ionization). High gains observed in He and Ne above 78 K are most probably due to Penning effect in uncontrolled impurities.

Conclusions

GEM structures can successfully operate at low T, even down to 2 K.

Stable and effective GEM operation was achieved in two-phase Ar at high gains, reaching 10^4, including in a single electron counting mode. These results are very promising for applications in coherent neutrino scattering and dark matter search experiments.

In two-phase Kr and Xe however the maximum GEM gains are limited, not exceeding 1000 and 200 respectively. In two-phase Xe in addition, the operation stability is still under question. For the time being, possible applications are limited to PET.

In He and Ne, the problem of the gain drop at low T can be solved by using the Penning mixtures of $He+H_2$ and $Ne+H_2$: very high gains, exceeding 10^4, can be obtained in these mixtures at T>10 K. Most probably high gains obtained at higher T in "pure" He and Ne are achieved by Penning effect in impurities. These results open ways towards two-phase and high-pressure cryogenic detectors for solar neutrino and coherent neutrino scattering experiments.

Outlook: physics of Cryogenic Avalanche Detectors

Physics of electron avalanching at low T:
- Ionization coefficients at low T
- Associative and Penning ionization at low T
- Avalanching in saturated vapor
- Electron and ion mobility at low T

Physics of two-phase media:
- Electron emission from liquid (solid) into gas phase
- Ion transport through phase interface
- Charging-up effects in the bulk liquid and at the phase interface

Physics of ion clusters at low T:
- Ion clustering
- Mobility of ion clusters

Estimation of ionization coefficients in dense noble gases using GEMs with narrow holes

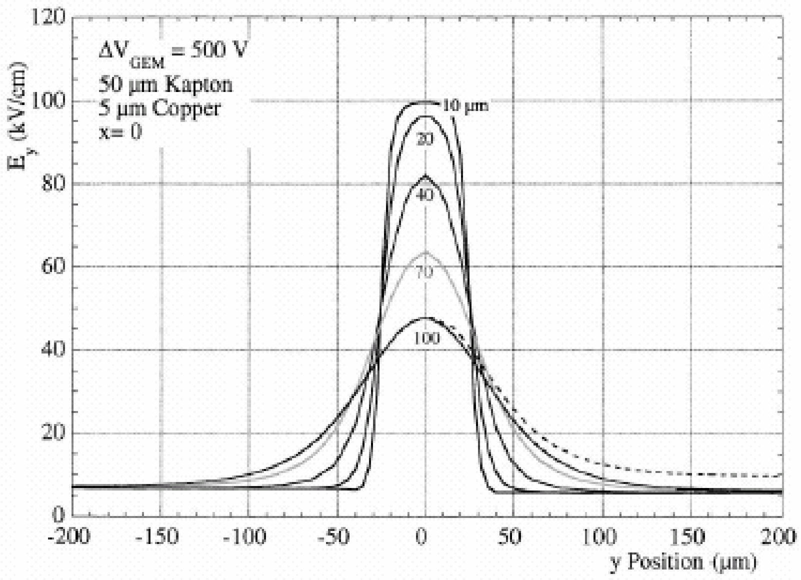


Fig. 10. Electric field computed along a line through the center of the holes, for different hole diameters.

Bachmann et al. NIM A 438(1999)376.

Parallel-plate approach:
works well for hole diameter below 40 μm:

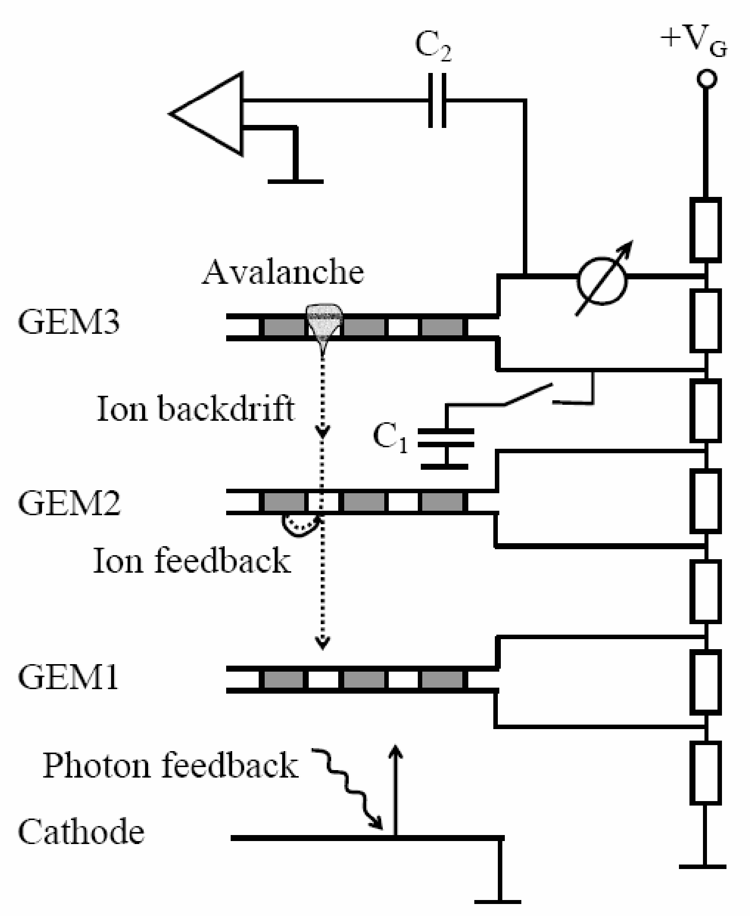
1. Gain of 1GEM configuration:
   $G = \exp(a\, d)$.

2. Ionization (Townsend) coefficient:
   $a / p = \ln G / (p\, d)$.

3. Electric field: computed value is taken in the center of the hole:
   $E = 80$ kV/cm at $\Delta V_{GEM} = 500$V.

See: Physics of multi-GEM structures, Buzulutskov, NIM A 494(2002)148.

Ion backdrift, ion feedback and photon feedback effects



- When C1 capacitor is off, the tail of anode pulse becomes substantially longer due to ion backdrift-induced signal: its width corresponds to ion drift time between GEMs
- This would allow to estimate ion mobility at high densities and low T.

See: Further studies of cryogenic avalanche detectors based on GEMs, Bondar et al., NIM A 535(2004)299.